Relation Between Soil Erosion and Sediment Yield in Catchment Scale

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ABSTRACT

Personal investigations of sediment balance show that in the case of diffuse sediment input in surface water, the quantity and the fraction of sediment sources (soil erosion, wash-off from unpaved surfaces, channel erosion, etc.) strongly fluctuate according to the landscape properties of the research areas. The spatial and temporal dynamics of sediment movement is therefore more detail analyzed. The investigation is located in the two landscape units of the Swiss Jura Plateau (clay-rich soils) and the loess-covered quaternary rolling countryside of the High Rhine valley. The investigation is based on the sediment balance. Special attention is paid to environmentally relevant nutrients, which are transported in particulate form and facilitate the tracing of sediment sources (e.g. phosphorous (PO_4), organic carbon (C)).

Sediment yield pattern represents sediment balance activities in a catchment and reflects the dominating processes therein. For this reason, the hydraulic removal of eco-functional matter (such as C and P) is monitored closely. Besides balancing sediment yield and improving analytical methods, we investigate whether sediment analysis could facilitate the tracing of sediment sources. We were thereby able to create several methods for sediment source identification. The investigations reflect the real need, in landscape planning, for instruments and methods, that enable an efficient location of areas which definitely contribute to water pollution, i.e. which have an above average sediment yield.

INTRODUCTION

Recent research activities for soil erosion and related processes have focused on bridging spatial and temporal discontinuities between field, hillslope and catchment observation scales. Recent interest in the potential impact of climatic change has emphasized the importance of investigating the production and translocation of sediment and sediment-bound pollutants at the regional and river basin scales, over an extended period of time (Garbrecht et al., 1995). Personal investigations of sediment balance show that in the case of diffuse sediment input in surface water, the quantity and the fraction of sediment sources (soil erosion, wash-off from unpaved surfaces, channel erosion, etc.) strongly fluctuate according to the landscape properties of the research areas.

At the catchment level, preferential flow-lines increase in significance due to natural and artificial linear elements in the landscape. Tractor spoors, rills and ditches, for example, are important conveyers of sediment. Hedges and grass strips, on the other hand, are landscape elements with high sediment retention potential (Schaub et al., 1997). The importance of ecological compensation areas and vegetative riparian zones for water conservation has been recognised (Braun et al., 1997).

For first-order catchments in Switzerland, Prasuhn (1991) and Mosimann et al. (1991) estimate the fraction of erosion to eventually enter a receiving stream is about 20% of the initial eroded material. They also estimate quantifiable accumulations to be about 40% of an erosion incident. Therefore, the remaining 40% of eroded material is randomly deposited on the field, on neighboring fields or along flow lines. However, runoff caused by low intensity rainfall can easily remobilize deposited material (Hairsine and Rose, 1992), as the cohesion between the particles is minimal ("clear-water effect"). The combination of factors present at points of intermediate accumulation determine the spatial range of sediment movement, the sediment input into surface water and thus ultimately catchment sediment loss.

According to several contributions at recent scientific conferences on soil erosion modeling (Meier-Zielinski and Rolli, 1997), simple empirical approaches based on USLE are able to approximate long-term erosion risk, but cannot be used to quantify range, flow lines or sediment yield. Long-term erosion averages do not reflect the "low frequency-high magnitude" phenomenon of soil erosion. Sediment translocation in the chorological dimension is particularly affected by extreme rainfall events, as large distances can be covered, up to and including streams. For the analysis of singular events, dynamic and deterministic erosion models are most appropriate, as relevant processes such as soil detachment; displacement and deposition are described in terms of physical relationships. Site-specific components and parameters are integral parts of these models. Due to complicated parameter setting, physical models are only suited for zero-order catchments and first-order catchments. Well-established methods and models for assessing processes between single events and long-term studies are, at present, unavailable (dynamic modeling at catchment level).

The revision of the Swiss Environmental Protection Regulation of 21.12.1995 (Schweizerischer Bundesrat 1996) includes an amendment of the decree on soil bound pollutants (VSBo) to the decree on soil stress (VBBo). According to Article 6, therein, provision has to be made to

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avoid permanent physical soil damage. Specifically in connection to soil erosion, a maximal soil loss tolerance value may not be exceeded and the retention of soil fertility may not be endangered. In Switzerland, the estimation of soil loss rates is based on the United Soil Loss Equation (USLE). This method enables a rough estimate of erosion risk based on static attributes (Mosimann and Rüttimann, 1996; Schaub and Prasuhn, 1998). Sustainable soil utilisation and the reduction of soil erosion are also mentioned in connection with water conservation in the revised agricultural policies (Schweizerischer Bundesrat, 1996). For this reason, 3m wide buffer strips in the riparian zone are necessary for fulfilling the requirements of integrated production (Art. 31 b LWG). With the extensive use of these zones, diffuse nutrient input in fluvial ecosystems is expected to be reduced. However, in order to enable efficient planning of vegetative riparian zones and ecological compensation areas, a better understanding of the degree to which preferential flow lines and riparian zones affect sediment yield is required.

LITERATURE REVIEW

For more than twenty years, the research group "Fachgruppe Bodenerosion Basel" (FBB) has conducted geoecological investigations. All research projects associated with this programme have a common thread: a quantitative description of environmental relationships can only be successful if a holistic approach is adhered to, and if the interaction of test site and model results are sought after.

Due to the continuity upheld in our research work and the adherence of a common principle, a wide range of experience could be gained on sediment balance mechanisms under natural and experimental conditions. Models of sediment and water regimes were developed and now serve as the basis of presenting translocation processes in the landscape dimension (e.g. Hosang, 1993; Huber, 1993). Consecutive projects analyzed the relationship between soil erosion and the reduction of crop yield of single fields (Schaub et al., 1998) With the combination of natural characteristics in the landscape balance (rainfall erosivity, soil texture, soil depth, topographic forms, land-use etc.), the soil erosion risk in the chorological (meso-scale) dimension could be modeled with the help of GIS techniques (Rolli, 1996). Further projects included nation-wide estimations of soil erosion (Schaub and Prasuhn, 1998). In projects, where a combination of statistical characteristics in the ecosystem were necessary, sediment fluxes in the chorological dimension were briefly mentioned. The current PhD thesis focus on sediment sources relevant in the chorological dimension (Meier-Zielinski and Rolli, 1997; Seiberth et al., 1997). Because the sediment yield in receiving streams represents sediment balance activities in a catchment and reflects the present condition and the dominating processes therein, the hydraulic removal of eco-functional matter was more closely monitored in recent sediment balance research activities. Besides balancing sediment yield and improving analytical methods, we also investigated whether sediment analysis could facilitate the tracing of sediment sources. We were thereby able to greatly improve the interpretation of flood sedigraphs and develop

several methods for sediment source identification (Dällenbach, 1996; Seiberth et al., 1997).

Actual Research plan

The study area is located in the research areas of the upper Ergolz valley (Länenbachtal, Swiss Jura Plateau, clay rich soil, 2.7 km^2, extensive agricultural utilization) and around the village of Möhlin, in the High Rhine Valley (0.7 km^2, loess rich soil, intensive agricultural utilization) as there are existing long-term databases of former research projects for these areas. Distinct soil substrate and land-use patterns result in noticeably different soil loss rates, sediment movement, and sediment delivery ratios [SDR].

The results of long-term soil erosion research laid the basis for the actual research project. According to these results, soil erosion contributes minimally to sediment yield on the Jura Plateau. On the loess-covered high terrace of the test-site "Möhliner Feld" a large percentage of the soil loss is transported off field (Table 1). As the soil loss rates of the fields in „Möhliner Feld" are noticeably higher than those in the Jura Plateau, the difference between the two test regions concerning sediment yield is striking (Schaub et al., 1997). The low SDR of the Jura Plateau is remarkable because of the dominance of rill erosion in clay. Thus, long flow distances are to be expected. As the drainage density is high, it was presumed that a close link exists between the eroded field and the receiving stream. On the other hand, the high sediment yield in the loess test-site was unexpected, as there are no perennial streams.
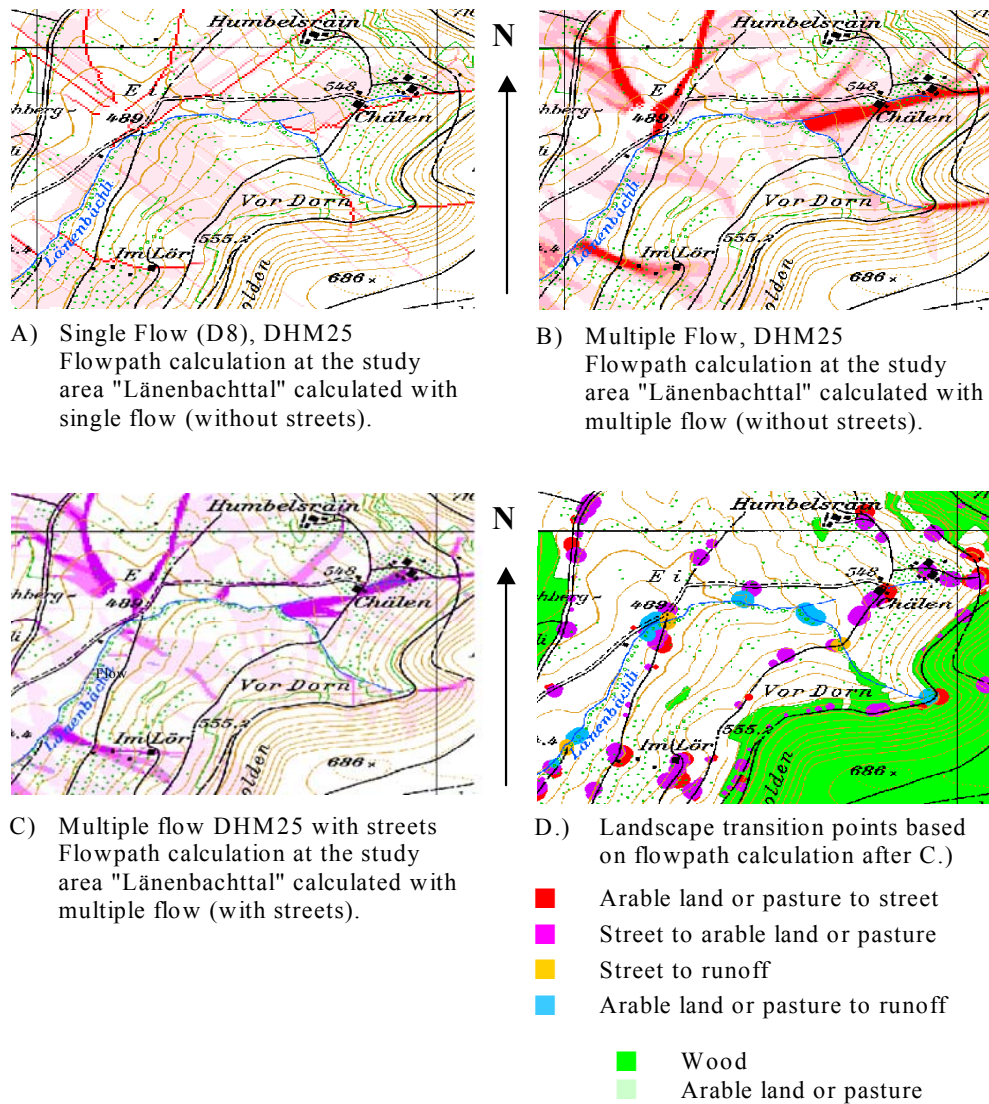
Table 1. Long-term medium values of the soil loss rates, the sediment loss of the catchment (registrated at the gauging station P50) and the sediment delivery ratio (SDR) of the two investigation areas.

Area	Soil loss rate [t*ha^{-1}*a^{-1}]	Catchment sediment loss [t*ha^{-1}*a^{-1}]	SDR [%]
Möhlin	4.9	1.85	37.76
Jura	0.93	0.271	29.14

The primary task of our research project is to explain the difference in behavior between the two test-sites with the help of monitoring and models. Special attention will be paid to flow lines and the retention potential of landscape elements. Broadening the focus from processes on an individual plot to the whole catchment requires the incorporation of other sediment sources, besides that of soil erosion. For this reason, wash-off and erosion from paved farm roads, as well as fluvial erosion and remobilization of temporary accumulations need to be included. Elements, like phosphorous and carbon, bind with fine sediment fractions, and are transported in particulate form, thus being suitable indicators of the activities on the test-sites. The sediment balance in different geo-ecological dimensions (erosion plot, mobile sediment troughs and sediment yield) will therefore form the basis of our research.

METHODS AND PRELIMINARY RESULTS

In the initial phase of the investigations, the sediment sources, preferential flowlines and landscape transition

A) Single Flow (D8), DHM25
Flowpath calculation at the study area "Länenbachttal" calculated with single flow (without streets).

B) Multiple Flow, DHM25
Flowpath calculation at the study area "Länenbachttal" calculated with multiple flow (without streets).

C) Multiple flow DHM25 with streets
Flowpath calculation at the study area "Länenbachttal" calculated with multiple flow (with streets).

D.) Landscape transition points based on flowpath calculation after C.)

- 🟥 Arable land or pasture to street
- 🟪 Street to arable land or pasture
- 🟧 Street to runoff
- 🟦 Arable land or pasture to runoff

- 🟩 Wood
- 🟩 Arable land or pasture

Figure 1. The results of the sediment balance helps to calibrate and verify the models. Otherwise the models help to get knowledge about the main flow pathes and to install measurement equipment on the right place.

Figure 2. Gauging stations used at A.) "Möhliner Feld" (called "PC" and "PR") and B.) at "Länenbachtal" (called "P50") catchments.

Table 2. The table below shows the yield of the flood waves registered at P50 between 1997-1998.

Flood wave	Sediment Yield [t]	TOC yield [kg]	POC yield [kg]	DOC Yield [kg]	Direct Runoff [m³]	Ground Runoff [m³]	Total Runoff [m³]
1/97	8.2	558	416	140	15'179	3'489	18'669
2/97	1.9	163	124	38	6'334	3'319	9'654
3/97	0.4	32	20	12	1'045	911	1'957
4/97	1.0	88	75	13	2'086	435	2'522
5/97	0.8	100	72	27	3'051	647	3'699
6/97	2.1	322	216	105	9'865	3'133	12'999
7/97	25.3	893	743	150	19'907	10'924	30'831
8/97	0.1	22	9	12	6'631	–	6'631
9/97	137.3	1'024	835	189	46'968	22'653	69'622
1/98	3.5	297	155	142	12'772	7'696	20'469'
2/98	4.8	431	281	149	15'840	9'722	25'563
3/98	1.2	74	35	39	3'821	3'227	7'049
4/98	152.1	517	381	138	12'506	14'363'	26'869
5/98	19.2	135	103	31	3'333	13'158	16'491
6/98	8.4	286	175	110	12'832	21'499	34'331
7/98	0.6	35	18	16	3'112	–	3'112
8/98	2.2	104	32	72	15'137	120	15'258
9/98	0.2	21	1	20	2'368	3'134	5'503
10/98	0.3	46	4	43	4'213	2'794	7'008
11/98	0.7	48	7	43	5'691	3'518	9'210
12/98	3.1	71	16	55	7'222	3'593	10'815
13/98	1.8	46	9	37	3'703	2'420	6'123
14/98	27.8	120	34	88	9'372	8'124	17'497
15/98	0.4	28	5	22	7'268	–	7'268
16/98	2.4	25	6	19	13'947	–	13'947
17/98	2.4	38	11	27	3'750	6'015	9'765
18/98	10.8	103	15	87	18'172	10'297	28'469

points linking runoff with drainage systems were identified and classified. Subsequently, suitable monitoring nodes were defined at typical landscape transition points (dust road to stream; field plot to stream; meadow to stream; street to stream. (Figure 1)). For an exact investigation of the water balance properties, it was necessary to collect water samples and monitor flow. Therefore, gauging stations were installed at suitable locations (Figure 2). Different kinds of gauging stations were installed for the measurement of the catchment loss in the investigation areas (at the "Möhliner Feld" two gauging stations were installed to measure the episodical runoff in the loess-area (they were called "PC" and "PR", in the "Länenbachtal there was just one gauging station installed called "P50"). For the registration of the water level, a mechanical level recorder (HKW - Groundwater level recorder, ALPINA HYDROMETRIE) was installed. For water samples of flood waves, an automatic water sampler (ISCO - Sampler Model 2700) was installed, together with an highly sensitive flowmeter (Model ISCO-2870). In the study area "Möhliner Feld", two neighboring catchments were defined (called "PC" and "PR"). Flumes were installed in both areas, following the example of the HS- and H-channels of the U.S. Department of Agriculture and Soil Conservation Service (USDA). Both flumes are equipped with ISCO-samplers and ISCO- flowmeters. It is therefore possible to quantify the periodical discharge and sediment translocation.

To investigate the variables and processes involved in diffuse sediment yield, several dimensions will be taken into consideration. Sediment yield is monitored once a week with the help of (bucket - samples) water samples, which will serve to define a basic sediment load. Furthermore, water samples from flood waves will be collected in high temporal resolution (24 automatic samples in temporal proportionality). Besides standardized parameters such as pH and electrical conductivity, the samples will also be analyzed for suspended sediments, phosphorous, nitrogen (NO_3), and organic carbon because they periodically affect water quality and are expected to facilitate the tracing of sediment sources.

Initial observations and sampling in the loess-region indicate that direct runoff from the high terrace to the low terrace is very often measured, but seldom causes (once or twice a year) large sediment yield at once. In the Jura Plateau, direct input of eroded material into the receiving stream is associated with much higher threshold values and occurs only during heavy and long during rainfall events. Most of the sediment loss only occurs during extreme events (Table 2). A direct link between eroded fields and the receiving stream is therefore rare in the Jura area, often in the "Möhliner Feld". Generally, in both catchments eroded material is accumulated temporarily on neighboring plots and is remobilized during subsequent rainfall events. Diffuse sediment input in receiving streams therefore takes place over several rainfall events (re-entrainment).

In our study, we also investigated whether catchment erosion could indirectly be described by means of the
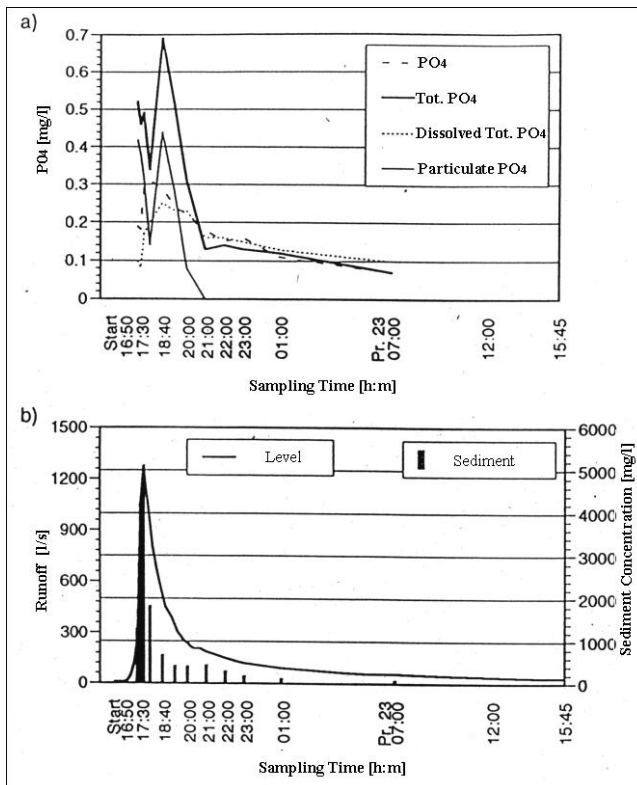
P 50 Flood wave # 5/98
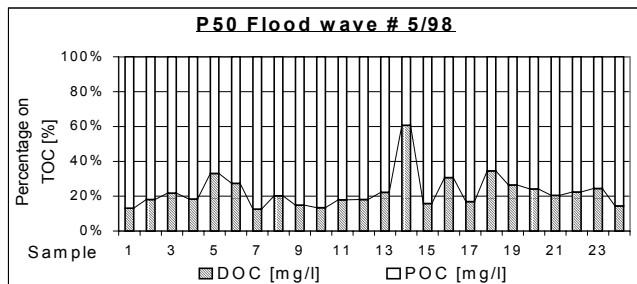
Figure 3A. Flood wave event with soil erosion in the catchment. The POC fraction contributes to more than 80% of the TOC yield.


P50 Flood wave # 9/98
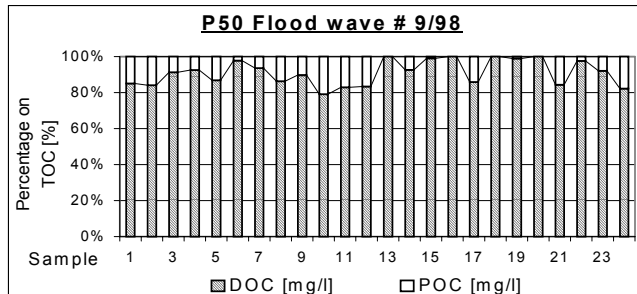
Figure 3B. Flood wave event without soil erosion in the catchment. The POC fraction is less than 20% of the TOC yield.

Figure 4. a) Phosphorous concentration recordings at a floodwave; b) Level and sediment concentration recordings at the same floodwave. (after: Dällenbach, 1996).

Table 3   Observed parameters at different points along the stream at the study area "Länenbachtal".

Observed Parameter	Sampling location		
	River near Drainage	Drainage	River at outlet P 50
Sediment [mg/l]	665.60	248.80	1860.00
DOC [mg/l]	2.95	3.58	4.12
POC [mg/l]	0.83	0.27	1.77
TOC [mg/l]	3.79	3.74	5.83
PO_4 Total [mg/l]	0.55	0.70	0.87
PO_4 Particulate [mg/l]	0.08	0.19	0.51
PO_4 Dissolved [mg/l]	0.47	0.51	0.36
PO_4 Ortho [mg/l]	0.43	0.52	0.39
NO_3 [mg/l]	14.11	17.69	17.95
Ammonium [mg/l]	0.03	0.02	n. A.
Conductivity [µS/cm]	0.34	0.25	n. A.

Flood waves 98 Comparision DOC
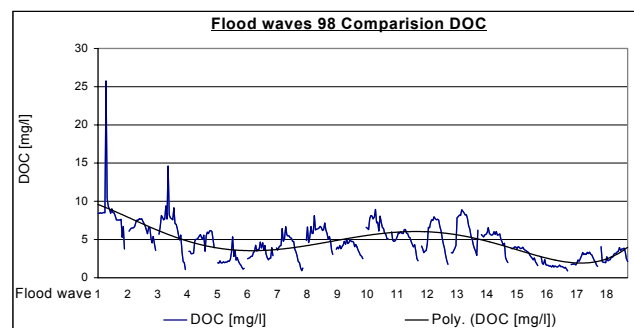
Figure 5. Figure above shows the behavior of DOC during the recorded flood waves 1998.

differential measurement of hydrological phosphorous and organic carbon yield. If the behavior of particulate organic carbon (POC) and dissolved organic carbon (DOC) is compared to the total amount of organic carbon yield during flood waves, it is apparent that there is a link between permanently high fractions of POC and soil loss in the catchment (Figure 3). It can thus be said, that carbon recordings and their presentation in percentages of POC and DOC of Total Organic Carbon (TOC) yield give a clear picture of the erosion-taking place in a catchment. However, the findings do not assist the location of sediment sources.

Phosphorous output recordings facilitate further differentiation and interpretation of integral signals of the receiving stream. As runoff results in soil erosion as well as stream erosion, the concentration of dissolved and particulate phosphorous will increase, as the runoff variable increases. The highest particulate phosphorous concentration during a flood wave only occurs once the maximum suspended sediment concentration has been attained (Dällenbach, 1996), allowing only a weakly significant relationship between the two variables (Figure 4). It can thus be assumed, that in the initial stages of a flood wave, phosphorous-deficient material from the channel itself is mobilized, before the fertilizer enriched and process enriched topsoil (high P-concentration) of fields and transitional depositions is recorded (Wilke and Schaub, 1996). It is therefore possible to identify sediment sources on the basis of particulate phosphorous output recordings.

Table 4. Annual sediment yield and runoff for the period 1997 and 1998 at "Länenbachtal", Swiss Jura Plateau.

	Base runoff	Flood runoff
1997		
Sediment yield [%]	4.1	95.9
TOC yield [%]	30.5	69.5
POC yield [%]	15.6	84.4
DOC yield [%]	57.8	42.2
1998		
Sediment yield [%]	5.9	94.1
TOC yield [%]	48.5	51.5
POC yield [%]	25.9	74.1
DOC yield [%]	61.7	38.2

Because of the clay rich soil in the Jura, the investigation area Länenbachtal is intensively drained. First observations suggested, that the drain system contributes a lot to nutrient input in the aquatic system (Table 3). Further investigations will focus on the influence of drain systems for the nutrient loss.To get knowledge about the main losspath of the focused matter, it can help to compare the yield and assign it to the runoff component (Table 4) or to compare the behaviour of the focused matter during the flood waves (Figure 5).

Comparisons of the yield and assignment to the runoff component can help to get knowledge about the main losspath of the focused matter. If high yield and increased concentrations are measured in flood runoff, there are grounds for the assumption that there is input of eroded material into the stream (input over main loss path "surface runoff" and "erosion"). If main yield is measured over base runoff and no increase of concentrations in flood runoff, there are grounds for the assumption that the input into the stream happens over "subsurface flow" and "groundwater flow".

DOC- concentration always increases after a little retardation to discharge during the flood wave. The delay is probably the result of additional DOC-enriched discharge from the soil solution. A continuance of the carbon recordings could deliver further information about runoff input, groundwater discharge etc.

The presented investigation is still in progress and more results will be expected.

FUTURE STUDIES

Up to now, research on erosion risk and non-point source pollution of water courses concentrated on the processes affecting the arable fields themselves, strictly speaking, on the sediment yield sources. Thus, an approximately direct slope-stream linkage was presumed to exist, although for some time, detailed investigations of the complex succession of intermediate sediment storage and remobilization within a catchment have been requested (Walling, 1983). In Swiss cultural landscapes that have been strongly shaped by long-term human activity, the land-use pattern (e.g. the structure of the filed forms) plays an important role in controlling the range of lateral sediment movement. Within the project, we intend to quantify these effects with the help of GIS-based spatial analyses. This is an important step away from the topological dimension to the catchment scale process dimension.

With the two-compartment approach to modeling sediment translocation, a linkage between topological and catchment scale process modeling will be made. The empirical method facilitates the location of areas with high sediment yield potential for larger landscape units, at different times. The sediment translocation processes of a single event are analyzed within a limited range, by means of the physical model, before it is extrapolated, where appropriate, to the remaining landscape units. Up to now, physical soil erosion models at the level of catchments, were not verified in, nor adapted to, Swiss conditions. Only methods that enabled long-term assessment of soil erosion risk were applied. However, these models did not allow for event specific interpretation of soil loss rates, translocation paths, and yield magnitude. Since the declaration of the new decree on soil stress (VBBo, Schweizerischer Bundesrat 1996), officials do not have a suitable instrument or model to analyze and quantify soil translocation over several fields (talweg erosion being a special case), nor event specific soil loss rates. The physical models will be tested and adapted to Swiss conditions in the framework of this application. Thus, as was with the modeling of talweg erosion in the previous application, an important step will be made towards improving the situation.

In the light of a reorientation of Swiss agronomic policy ("Agronomic Policy 2002"), many changes are to be expected in the landscape pattern, in the next couple of years (intensive use of individual fields on the one side, definition of ecological compensation zones on the other). The proposed investigations therefore reflect the real need, in landscape planning, for instruments and methods, that enable an efficient location of areas which definitely contribute to water pollution, i.e. which have an above average sediment yield.

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